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# OFF-ROTOR WELD REPAIRS TO NANTICOKE TGS LP TURBINE BLADES

Report No 88-77-K

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## ABSTRACT

Leading edge cracking on martensitic stainless steel low pressure turbine blades has been repaired, off-rotor, with the gas-tungsten-arc welding process. This report describes the step-by-step details of the repair procedure, and the results of a metallurgical and mechanical evaluation of the effects of the repair on overall blade integrity. Although we believe that these repaired blades would not yet be suitable for use in production, the information gained from this work is one step towards the eventual development of an in-situ or on-rotor repair welding technique.



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EXECUTIVE SUMMARY

# OFF-ROTOR WELD REPAIRS TO NANTICOKE TGS LP TURBINE BLADES

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As part of a program of developing weld repair technology for martensitic stainless steel (or 12% chromium) steam turbine blades, the Welding Unit of Research Division is assisting Central Thermal Services of Technical & Training Services Division, by evaluating an off-rotor weld repair procedure. The long-term objective of the overall project is to determine the viability of an in-situ, or on-rotor, welding repair option for airfoil cracking.

In the present work the step-by-step weld repair of three Nanticoke TGS low pressure blades, with leading edge airfoil corrosion fatigue/stress corrosion cracking, is described. Also discussed are the results of metallurgical evaluation and mechanical property tests which indicate that the repaired blades have been weakened to below manufacturer specified strength values, in areas outside of the weld zone due to overtempering. The weld repairs themselves, however, do appear to be sound and properly heat treated.

The information gained in this development work should be very useful in terms of achieving the goal of in-situ blading repair, and several detailed recommendations have been included. Further study into mechanical testing, post-weld heat treatment, non-destructive evaluation, and distortion measuring has been suggested.

It should be noted that the 12-chrome family of steels is in common use in Europe for other thermal plant components (besides rotating blade equipment), such as steam pipelines, valves, turbine casings and bolts. The higher creep strength of these steels, compared to most low alloy ferritics (i.e. 1 Cr Mo, 1/2 Cr Mo V, 1 Cr Mo V and 2.1/4 Cr Mo), allows the use of thinner sections and a reduced support system, or increased steam pressures and/or temperatures. In the future, the use of the 12-chrome alloys may become more common in Ontario Hydro's thermal power production facilities, and consequently their welding and fabrication could become a topic worthy of more detailed study.



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# OFF-ROTOR WELD REPAIRS TO NANTICOKE TGS LP TURBINE BLADES

J.G. Galloway

## 1.0 INTRODUCTION

As part of a program of developing weld repair technology for martensitic stainless steel steam turbine blades, the Welding Unit of Research Division is assisting Central Thermal Services of Technical & Training Services Division, by evaluating off-rotor repairs made by a local specialized welding contractor. The long term objective of the overall project is to determine the viability of an in-situ, or on-rotor, welding repair option for airfoil cracking.

Three visibly cracked Nanticoke TGS-4th stage turbine blades were selected for repair. Each blade had leading edge corrosion fatigue/stress corrosion cracking. These blades were machined from NEI-Parsons Specification No 29H material (see Table 1 for composition requirements) which is a modified type 410 martensitic stainless, or 12-chrome steel, forging. The Gas Tungsten Arc Welding (GTAW) process was to be used for repair and a filler metal with a closely matching composition to the blading (see Table 1) was selected.

This report will detail the initial blade inspection, crack removal and weld preparation, the welding procedure, post-weld heat treatment (PWHT), weld inspection, airfoil reprofiling, blade distortion measurements, and finally the metallurgical evaluation of the repair. Mechanical testing was also performed on the airfoil material outside of the repair area to help measure any effects of the additional thermal aging heat treatment that these areas received. Note that a complete re-austenitization of the blade, followed by tempering, would not be practical in-situ, because of heat losses into the turbine rotor.

## 2.0 REPAIR PROCEDURE

### 2.1 Initial Blade Inspection

Each blade was first inspected with the Liquid Penetrant Inspection (LPI) technique in order to determine the full extent of the airfoil cracking. The blades were labelled A, B and C and the inspection results are listed below:

(Note: all cracking was found on the airfoil leading edge only, running generally perpendicular).

Blade A - (one crack) - 9 mm long; 78 mm from the tip.

Blade B - (crack No 1) - 9 mm long; 32 mm from the tip.
(crack No 2) - 11 mm long; 54 mm from the tip.
(crack No 3) - 8 mm long; 66 mm from the tip.

Blade C - (one crack) - 4 mm long; 33 mm from the tip.

### 2.2 Welding Contractor

A reputable Toronto area welding shop was contacted for their opinion on the repair welding. This specialized repair and fabrication shop has had experience in repair welding of gas turbine components for the aircraft industry, including work on blading. In their opinion, repair welding was feasible and they were contracted to do the crack removal and repair welding.

### 2.3 Crack Excavation

The cracking was removed from the blades using a 4.5 inch diameter disc angle grinder. The rotating disc was powered into the crack on its edge leaving a deep, narrow excavation. The blades were then given an LPI by the welding contractor in order to confirm total crack removal.

At this point the blades were returned to OHRD for measurements and photography. Each excavation was wet sanded using a 120 grit silicon carbide paper in order to remove grinding burrs and then was re-inspected with the LPI technique. Four of the cavities (B1, 2 and 3 and C) showed linear indications at their tips as shown in Figures 1a and 1b. The explanation for the presence of cracking to this depth was not clear. It was thought that the cracks were extending due to the stresses raised by the heat of grinding, or perhaps that the original inspection did not reveal the true depth of the cracking. The failure of the welding contractor's inspection in detecting these crack tips may be explained by the presence of grinding burrs in the cavity, blending over the discontinuities.

These two blades (B and C) were returned to the welding contractor for further crack removal with the same technique. Subsequent LPI at OHRD, following burr removal, confirmed total crack excavation. The resulting weld preparations are shown in Figures 2a to 2c.

These excavations were very deep and narrow; for example, the cavity in blade C was 19 mm deep and only approximately 3.5 mm wide. Discussions were held with CTS personnel and it was decided that a wider preparation would be necessary to ensure complete side fusion in the weld repairs. Further excavation was then undertaken at OHRD, again with a grinding technique, and after sanding and LPI, the finalized weld preparations are shown in Figures 3a to 3d.

## 2.4 Repair Welding Procedure

As part of the welding procedure, a preheat temperature of 230°C was selected, and a maximum interpass temperature of 370°C was specified. The GTAW process was employed using a 100% argon shielding gas and a 1.6 mm dia EWTh-2 electrode. No auxilliary or side shielding gas coverage was used. The welding power source was set to 90 amperes maximum current output (DCSP) and was foot-controlled below this value as required. The filler metal selected was 1.6 mm dia ER410 Ni Mo (ASME Spec No SFA-5.9).

Each blade was cleaned and degreased with acetone before welding. Preheating was performed with an oxyfuel torch, and the blade's temperature was intentionally increased relatively slowly. Preheat and interpass temperature was confirmed with temperature indicating crayons. The welding technique used a combination of longitudinal and transverse (to the length of the airfoil) stringer beads to gradually weld out the cavity. Heat input was kept to a minimum. Upon the completion of welding the blades were immediately buried in preheated sand for slow cooling to room temperature.

## 2.5 Post-Weld Inspection

The welded blades were returned to OHRD for PWHT, reprofiling and evaluation. Before PWHT the blades were inspected using the LPI method. Although the surface of the repairs appeared relatively rough (see Figures 4a-4c), and slightly discoloured from welding, there was no indication of open weld defects or airfoil cracking.

## 2.6 Post-Weld Heat Treatment

The three repaired turbine blades were given a PWHT together in an air atmosphere furnace. The rate of temperature rise was controlled to a maximum of 100°C/hour and a hold temperature of 650°C for two hours was selected. The hold temperature accuracy was ± 5°C (monitored with thermocouples). A furnace cool to room temperature followed the holding time. After PWHT the blades were reinspected with the LPI method. No defects were found.

## 2.7 Airfoil Profiling

Excess weld metal from the repairs was removed simply with a combination of grinding with coarse and then fine aluminum oxide stones on a die profiler (as is used in metal forming die manufacturing). Final removal was with a 120-grit silicon carbide paper. The resulting airfoil profile was very smooth although the presence of the weld repairs could still be detected as very slight bumps.

## 2.8 Final Weld Inspection

Both LPI and radiographic inspection were carried out as final inspections to the profiled weld repairs. The radiographic technique used had a better than 2% of thickness detection sensitivity. All of the repaired cavities and the surrounding material appeared sound to both these inspection techniques.

# 3.0 METALLURGICAL EVALUATION OF THE WELD REPAIRS

The weld repair areas were removed from the blades and mounted flat on their concave side. These sections were then ground to the approximate centre line of the blade thickness and prepared for metallographic examination. Vilella's Reagent was used as the etchant for all the polished samples in this investigation. The etched macroscopic cross-sections are shown in Figures 5a-5c. In addition, Vickers hardness testing with a 2.5 kg load was performed on these samples.

The microstructure of the weld deposit in blade C is shown in Figures 6a and 6b at 200 and 1000 X magnification, respectively. At the lower magnification an acicular tempered martensitic structure is visible, while at the higher magnification coarse dispersed alloy carbides are apparent in the fine martensitic lath structure. This microstructure is generally consistent throughout the depth of the repair. The hardness testing results in this deposit also indicate homogeneity with an average value of 301 Hv and little variation through its depth. Similar average hardness values were found in the other weld deposits.

The microstructure of the heat-affected zone (HAZ) of weld C (as shown in Figure 6c at 1000 X magnification) is tempered lath-type martensite within prominent prior austenite grains. Alloy carbides are generally finer than those found in the weld deposit and no delta ferrite or untempered martensite was visible. Hardness testing results in the HAZ of all the deposits found a maximum value of 327 Hv.

# 4.0 OVERALL EVALUATION OF THE BLADES

## 4.1 Metallurgical Evaluation of the Airfoil

A sample of the airfoil of blade C was removed for metallurgical examination. This section was taken well away from the area of the weld repair (see Figure 7) in order to evaluate the condition of the base metal following the PWHT. The sample was mounted, polished, and then etched with Vilella's Reagent.

The microstructure was revealed to be very heavily tempered martensite (see Figure 8a). Almost no evidence of the prior austenite grain boundaries can be found, and the carbides are large and widely dispersed. No free ferrite was visible.

Along the edges of the blade exposed to the air atmosphere PHWT there was concern expressed about possible decarburization. High magnification optical examination of this area was difficult because of the polishing effect of edge rounding. At lower magnifications, as shown in Figure 8b, a lighter microstructural band runs parallel along the exposed edge. Also visible in this micrograph is a Knoop microhardness survey to this edge (using a 100 g load). It would appear from the microhardness survey that no appreciable decarburization has taken place as the readings are all very close to an average value of 306 Knoop. Through the use of scanning electron microscopy this light microstructural region at the edge was confirmed to be only a polishing effect.

## 4.2 Room Temperature Mechanical Properties

Samples were removed from the airfoil of blade C (as illustrated in Figure 7) for an evaluation of PWHT on hardness, tensile properties, and room temperature Charpy 'V' notch impact toughness. Comparisons were made of these values to those specified by the turbine manufacturer in previous work/1/, in their material specification for these blades, and to those found in previous failure analysis work on this type of blade at OHRD/2/.

The hardness measurements were made on the impact samples using both the Vickers (2.5 kg) and the Rockwell C methods for comparison. The tensile testing was performed on sub-size number 12 Hounsfield specimens. All of the mechanical testing results are listed in Table 2.

## 4.3 Airfoil Distortion

In order to measure the effects on blade shape of the repair procedure a special jig was assembled (see Figure 9a) which clamped onto a blade at its root and measured the airfoil at four points with dial indicators (see Figure 9b). Using a zeroing blade (i.e. a control blade without cracking) as a calibration device, this jig was found to have a repeatability of $\pm$0.08 mm ($\pm$0.003 in.)

Comparative measurements of the blades undergoing repair were made at each critical point in the repair procedure as listed below:

1. As-received
2. After crack excavation
3. After welding
4. After PWHT
5. After reprofiling.

The results of these measurements indicated that at no point in the repair procedure did any of the measured values vary more than 0.86 mm (0.034 in.) The only point on the blade that showed any substantial movement was the slight inward rotation of the trailing edges of the airfoils during PWHT. Also, no detectable trailing edge warping was found.

## 5.0 DISCUSSION

### 5.1 Inspection Techniques and Defect Excavation

The difficulties that were encountered in our attempts at complete crack excavation are likely indicative of our failure in determining the true extent of the cracking during the initial inspection. In the failure analysis work at OHRD/2/ on this type of blading, it can be seen that a duplex oxide corrosion product fills the crack opening, especially at the tips, when this stress corrosion and corrosion fatigue mechanism is encountered. Under these conditions the LPI technique may then not be a suitable inspection method as the penetrant will not enter an oxide-filled crack with great success. Consideration should then be given to a radiographic or magnetic particle inspection (MPI) technique (especially fluorescent) for the determination of crack length in the initial inspection.

For excavation, the disc grinding method may seem heavy handed and crude, but armed with knowledge of the true depth of the cracking, it should be quite an acceptable technique, provided that it is acceptable for some overheating to occur. Note that burrs from grinding should be removed before inspecting the excavation for unremoved cracking with the MPI method. The wider weld preparations that were specified (compare Figures 2 and 3) are simply a more conservative approach to ensuring full side fusion in the repair weld.

For post-weld inspection the techniques employed (i.e. LPI and radiography) are probably sufficient although we do have reservations on the detectability of internal side fusion discontinuities. This is a defect type which was not encountered in our cross-sectional observations, but which we believe this shape of repair could be prone to, especially when the weld preparations are narrow.

### 5.2 Welding Procedure

The use of high preheat temperatures of up to 450°C had been traditional practice when welding the 12-chrome family of alloy steels/3/. At these temperatures the weld is fully austenitic during welding, and the transformation to martensite was achieved by cooling the weldment to an intermediate hold temperature of between 100 to 150°C before PWHT. With this hold temperature, full martensite transformation is not expected, i.e. some residual austenite was tolerated in order to avoid hydrogen cracking and brittle fracture in the untempered martensite.

The preheat temperature used in the present study was 230°C, and the maximum interpass temperature was 370°C. At these temperatures the weld metal and HAZ are generally kept between the critical temperatures Ms and Mf (i.e. martensite start and martensite finish). This allows for the partial transformation to martensite of the weld deposit, and with subsequent weld passes, layer by layer tempering/3,4/. It is believed that this sequence of events, combined with the low hydrogen nature of the GTAW process, allows for the cooling to room temperature of the weld before PWHT begins, as the deposit is left martensitic, but sufficiently tempered to withstand the stresses of complete phase transformation and cooling without cracking. Another advantage of this procedure is the complete absence of retained austenite in the weld deposit, which would transform to brittle untempered martensite upon cooling from PWHT temperatures. Indeed there is some question as to the actual Mf temperature of deposited weld metal, which may be in the range of betweeen 50 to 150°C, depending on the thermal cycle peak temperature and exact filler chemistry, and some research has recommended that intermediate hold temperatures (if used) be as low as 50°C to avoid retained austenite/3/. As an alternative, a second PWHT can be used to ensure the tempering of any untempered martensite remaining from the first PWHT.

The filler metal used in the present study (ER410 Ni Mo), while being a close chemical match to the base metal, is not an exact match (see Table 1). Notable differences in alloying element content in the filler metal are:

- a lower specified carbon content;
- a higher specified nickel content;
- a lower specified molybdenum content;
- a lower specified manganese content;
- no specification on vanadium or niobium.

These differences, although they may appear to be slight, could have effects on the service life of the blade, as the reduction in the content of the strong carbide forming elements (as well as carbon itself) is most notable (i.e. Mo, V, Mn and Nb). The carbides formed by these elements are key in giving this material its superior creep resistance and other beneficial high temperature properties. Obtaining a more closely matching filler should be considered before further experimentation, or actual blade repairs are attempted. The 1.6 mm diameter type ER410 Ni Mo filler rod was procured, after an extensive supplier search, from a US company. For purchasing other filler metal chemistries, more success may be had if European manufacturers are contacted. Much of the data on the welding of the 12-chrome family of steels comes from West Germany and the UK where they are more commonly used in thermal power station components, including piping, exposed to high temperature and high pressure steam/3/.

## 5.3 Post-Weld Heat Treatment

The metallographic and hardness results from the repair cross-sections appear to indicate the success of the PWHT in achieving a fully tempered deposit and HAZ. The hardness profile throughout these regions was consistently between 296 and 327 Hv. As for the mechanical properties in this region, no testing was possible on these small deposits. Work in the US on a similar composition alloy steel (HT-9), which is being studied for possible use as first wall/blankets in fusion energy machines, does discuss various tests conducted on the HAZ of welds/5,6,7/. One study by Lippold/7/ includes Charpy V notch impact test results on thermally simulated HAZ microstructures, in the as-welded condition and after PWHT (at both 600 and 760°C for one hour).

As for the condition of the surrounding blade material, which has effectively received two thermal aging heat treatments at 650°C for two hours each (one being the original manufacturer temper, and the other being our PWHT), it appears to be overtempered. There is almost no optical trace of the original martensitic lath structure, or of the prior austenitic grain boundaries, and the carbides which are present are widely dispersed (see Figure 8a). In the mechanical testing that was performed (i.e. hardness, room temperature, Charpy V notch impact and tensile), a below specification reduction in tensile and yield strength from those values found in earlier OHRD work on the as-received blades/2/ is apparent. Little change was found in the toughness properties (see Table 2).

The implications of this loss of yield strength on the long term service life of the blades is projected to be a reduction in fatigue properties, although the lower hardness may be beneficial in terms of a decreased susceptibility to stress corrosion cracking/2/.

We suggest that alternative PWHT temperatures in the area of 600°C and/or shorter hold times be investigated. This would likely lead to a harder, less ductile weld deposit, but base metal that meets the specified mechanical property requirements.

Another suggestion is the investigation of a localized PWHT procedure such as an induction heating technique, in which the weld metal, the HAZ area, and only a limited amount of base metal, would be heated to the PWHT temperatures/8/. There should be no concern of temper embrittlement in the surrounding base material (where the hold temperature would be in the range of approximately 350 - 500°C) as the initial manufacturer's temper should have neutralized the embrittlement mechanism in these areas/9/. Concerns that we would have for such a localized PWHT are the presence of a band of possibly overtempered base metal surrounding the deposit, and the effect on blade distortion of spot heating.

It should be mentioned that although our PWHT was conducted in an air atmosphere, as would likely be the case in any field on-rotor PWHT, there were no apparent edge effects (such as excessive softening or microstructural change) on the blade's exposed edges.

### 5.4 Airfoil Distortion

Measurements made of airfoil distortion with our simple measuring fixture, although far from conclusive, do indicate that no major change in blade shape has taken place as a result of the repair procedure. Although a maximum allowable distortion level has not to our knowledge been clearly defined, we believe that a much more precise method of measurement would be necessary for future studies. Perhaps the use of a laser or contact coordinate system in conjunction with the development of a repeatable fixturing or reference holding device should be considered. Such a device would be capable of detecting trailing edge warping, such as was encountered in an earlier study/10/, and would give a much more comprehensive indication of the overall distortion being encountered. This type of equipment is used for the quality control of such things as automotive stampings, and is available for contract use in the Toronto area.

As previously mentioned, one future concern relating to distortion may be the implementation of a spot, or weld zone only, PWHT.

## 6.0 CONCLUSIONS

1. Leading edge cracking on three Nanticoke TGS LP turbine blades has been excavated and weld repaired, off rotor, using the GTAW process with filler metal similar in composition to the blade material. However, the selected PWHT (650°C for two hours) has reduced the ultimate tensile and yield strength of the base metal to below the minimum values specified by the turbine manufacturer. In the weld zone, the tempering appears to be sufficient.

2. There is a possibility that the Liquid Penetrant Inspection technique does not indicate the true depth of the corrosion fatigue/stress corrosion leading edge cracking encountered on these blades, because of a tight duplex oxide corrosion product which resides in the crack tips.

3. The use of a 230°C preheat temperature (with a maximum interpass temperature of 370°C), in combination with the low hydrogen and multipass GTAW process, seems to have resulted in a weld zone containing enough tempered martensite to withstand cooling to room temperature (before PWHT) without cracking. This room temperature cooling ensures the complete phase transformation of austenite to martensite in the deposit and HAZ. Without retained austenite there should be no danger of the formation of brittle untempered martensite after PWHT.

4. A simple airfoil distortion measuring jig was constructed which indicated only minor changes in blade geometry as a result of the repair procedure.

5. Exposure to air atmosphere PWHT appears to have no significant effect on microstructure or hardness along the blade edges.

## 7.0 RECOMMENDATIONS

This section highlights several recommended areas of future study into in-situ blade repair, as follows:

1. Mechanical Testing - More complete mechanical testing of weld deposits, thermally simulated HAZ's, and double tempered blade material should be considered. One researcher has stated that standard (blunt) 'V' notch Charpy testing on this material does not give a true indication of the state of embrittlement, and recommends the use of pre-cracked and instrumented Charpy impact coupons/9/. Other testing such as fatigue, elevated temperature tensile, and fracture toughness studies may also be required. For any of this work much more raw blading alloy material would need to be made available.

2. PWHT - Further study of lower PWHT hold temperatures and/or shorter hold times will be necessary to reduce the overtempering effects on the base metal outside of the repair area.

3. Localized PWHT - In an in-situ repair situation obtaining complete and even PWHT over the entire blade will be extremely difficult/8/. Consideration should be given to either an induction or spot resistance technique which heats only the vicinity of the repair welds.

4. Filler Metal - The purchase of a filler metal more closely matching the composition of the base metal may be necessary in order to maintain similar mechanical properties throughout a repaired blade.

5. Non-Destructive Evaluation - Further work on the best technique for initial crack depth determination should be considered (i.e. radiography or fluorescent MPI). Also, the ability of the radiographic inspection method in locating sidewall fusion defects should be questioned.

6. Distortion Measuring - A more accurate and comprehensive measurement system, such as a laser or contact coordinate device, should be considered for use in future repair studies.

7. Other Repair Areas - Only leading edge cracking has been repaired in our present work. Other cracking repairs, such as around the lacing wire holes or in the blade roots, and the build-up of erosion damaged areas, could be considered. Access to some of these areas in-situ will obviously be a problem and off-rotor repairs may be the only alternative.

8. Other Processes - The use of plasma or flame sprayed coatings as a crack preventive deserves further consideration. Also the use of powders in the repair cavity (either sintered or hot isostatically pressed) could be investigated. These processes have been studied for use in the repair of superalloy blades in the aircraft industry.

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TABLE 1 - CHEMICAL COMPOSITION SPECIFICATIONS (WT %)

| Element | Nanticoke TGS LP Blade* | Welding Filler Rod ** |
|---|---|---|
| C | 0.08 - 0.15 | 0.06 max |
| Cr | 11.0 - 12.5 | 11.0 - 12.5 |
| Ni | 1.50 - 3.00 | 4.0 - 5.0 |
| Mo | 0.70 - 2.00 | 0.4 - 0.7 |
| Mn | 1.00 max | 0.6 max |
| Si | 0.50 max | 0.50 max |
| Cu | - | 0.75 max |
| V | 0.05 - 0.40 | - |
| Nb | 0.10 - 0.40 | - |
| P | 0.03 max | 0.03 max |
| S | 0.03 max | 0.03 max |
| Fe | BAL | BAL |

* NEI-Parsons Material Spec No 29H
** ASME Spec No SFA-5.9 (ER410 Ni Mo)

TABLE 2 - MECHANICAL TESTING RESULTS

| Sample | HARDNESS HV | Rc |
|---|---|---|
| IA | 262 | 27.0 |
| IB | 263 | 26.5 |
| IC | 261 | 26.5 |
| OHRD (2) | 281(Root)-340(Tip) | - |
| NEIP (3) | 270 - 325 | - |

CHARPY 'V' (20°C)

| Sample | Impact Energy (J)) | Lateral Expansion(%) | Shear (%) |
|---|---|---|---|
| IA | 101 | 13.2 | 40 |
| IB | 98 | 11.7 | 40 |
| IC | 115 | 12.7 | 40 |
| OHRD(2) | 121 | 13.2 | 55 |
| Spec(4) | 54 min | - | - |

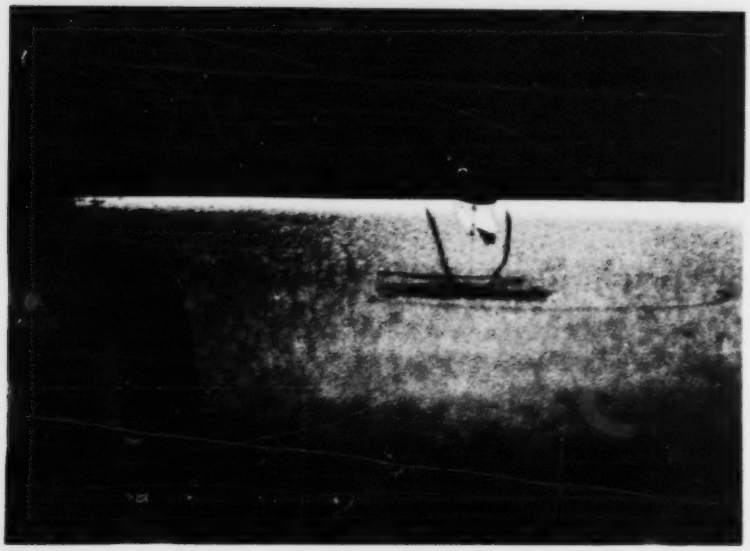
HOUNSFIELD No 12 TENSION TESTS

| Sample | UTS(MPa) | 0.2% PS(MPa) | % El on $4\sqrt{A}$ | % RA |
|---|---|---|---|---|
| TA | 794 | 649 | 27 | 62 |
| TB | 801 | 661 | 25 | 60 |
| TC | * | * | 25 | 60 |
| OHRD(2) | 946 | 827 | 18 | 62 |
| Spec(4) | 930-1080 | 770 min | 15 min | 40 min |

* recorder malfunction

Notes: (1) Samples from airfoil of blade C (see Fig.7) after welding & PWHT
(2) Ref /2/
(3) Ref /1/
(4) NEI-Parsons Material Specification No 29H.

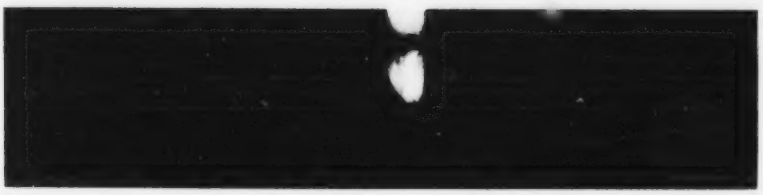
*1a - Blade B ($B_1$, $B_2$, $B_3$)*



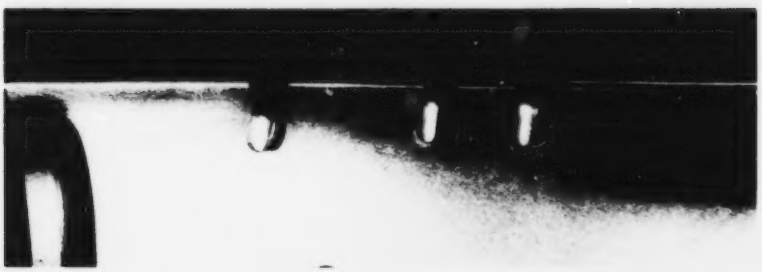
*1b - Blade C*

**FIGURE 1**

**LPI INDICATIONS REMAINING AFTER THE FIRST CRACK REMOVAL ATTEMPT (1.5 X MAG)**



*2a - Blade A*

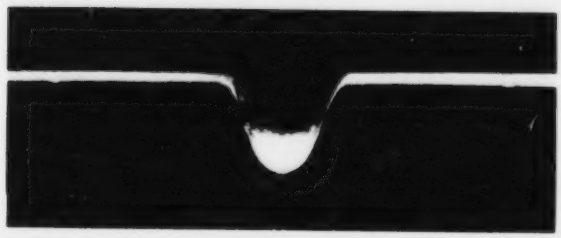


*2b - Blade B*

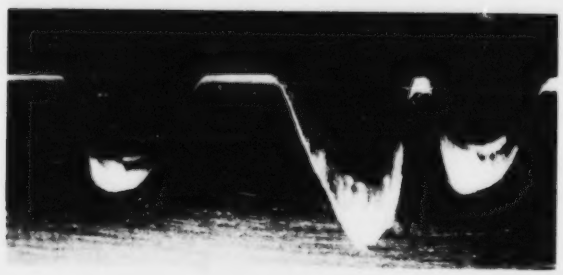
*2c - Blade C*

**FIGURE 2**
**WELD REPAIR CAVITIES BEFORE WIDENING**
**(1.5 X MAG)**

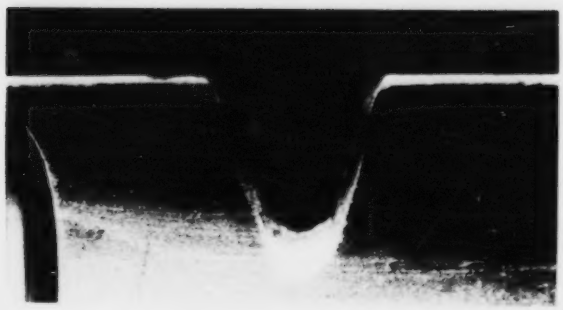
*3a - Repair Cavities (Blades C, B, A) (0.25 X Mag)*



*3b - Repair Cavity A (1.5 X Mag)*

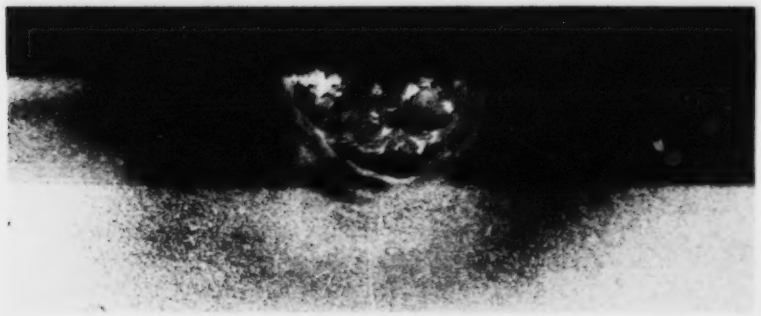


*3c - Repair Cavities ($B_1$, $B_2$, $B_3$) (1.5 X Mag)*



*3d - Repair Cavity C (1.5 X Mag)*

**FIGURE 3**
**FINAL WELD PREPARATIONS**

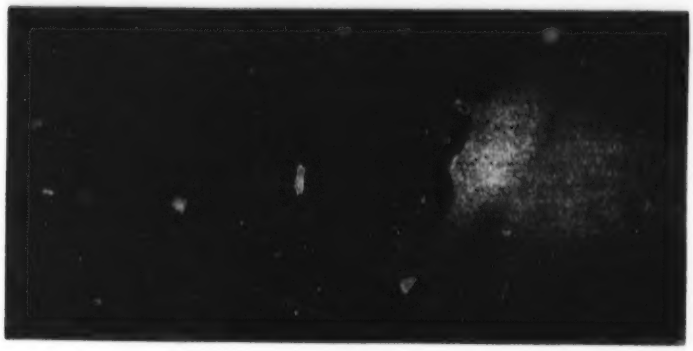


*4a - Blade A*

*4b - Blade B ($B_1$, $B_2$, $B_3$)*

*4c - Blade C*

**FIGURE 4**
**REPAIR WELD SURFACE APPEARANCE**
**(1.5 X MAG)**

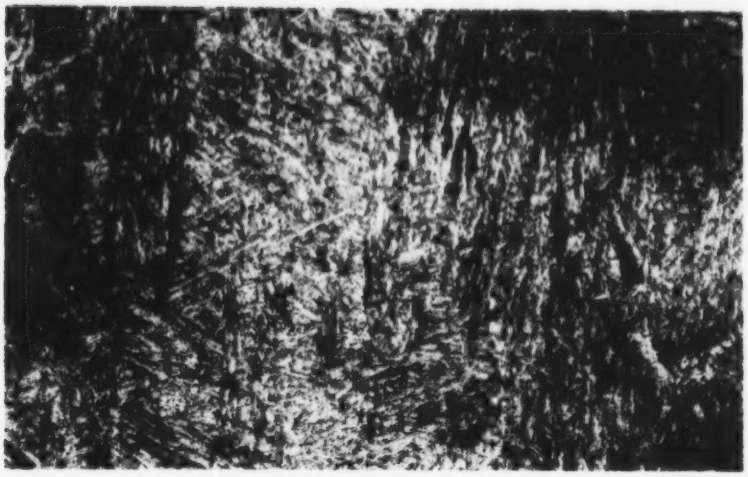


*5a - Repair A*

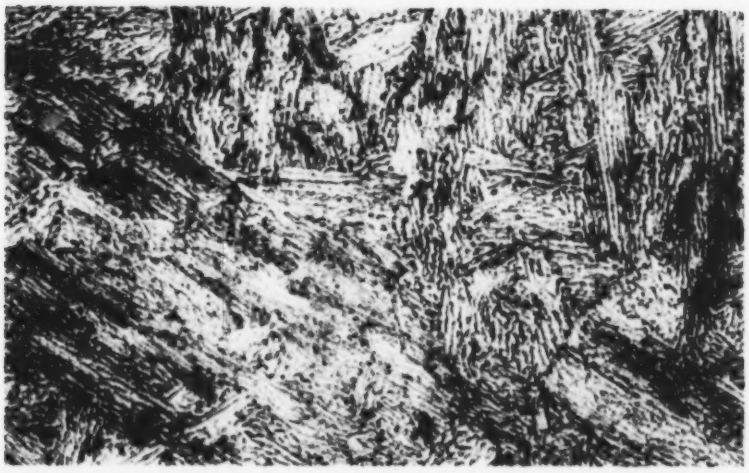
*5b - Repair Areas $B_1$, $B_2$, $B_3$*

*5c - Repair C*

**FIGURE 5**
**WELD REPAIR CROSS-SECTIONS**
**(3.5 X MAG)**



*6a*
*Weld Metal*
*(200 X Mag)*



*6b*
*Weld Metal*
*(1000 X Mag)*

*6c*
*HAZ*
*(1000 X Mag)*

**FIGURE 6**

**MICROSTRUCTURE IN THE WELD REGION OF REPAIR C**

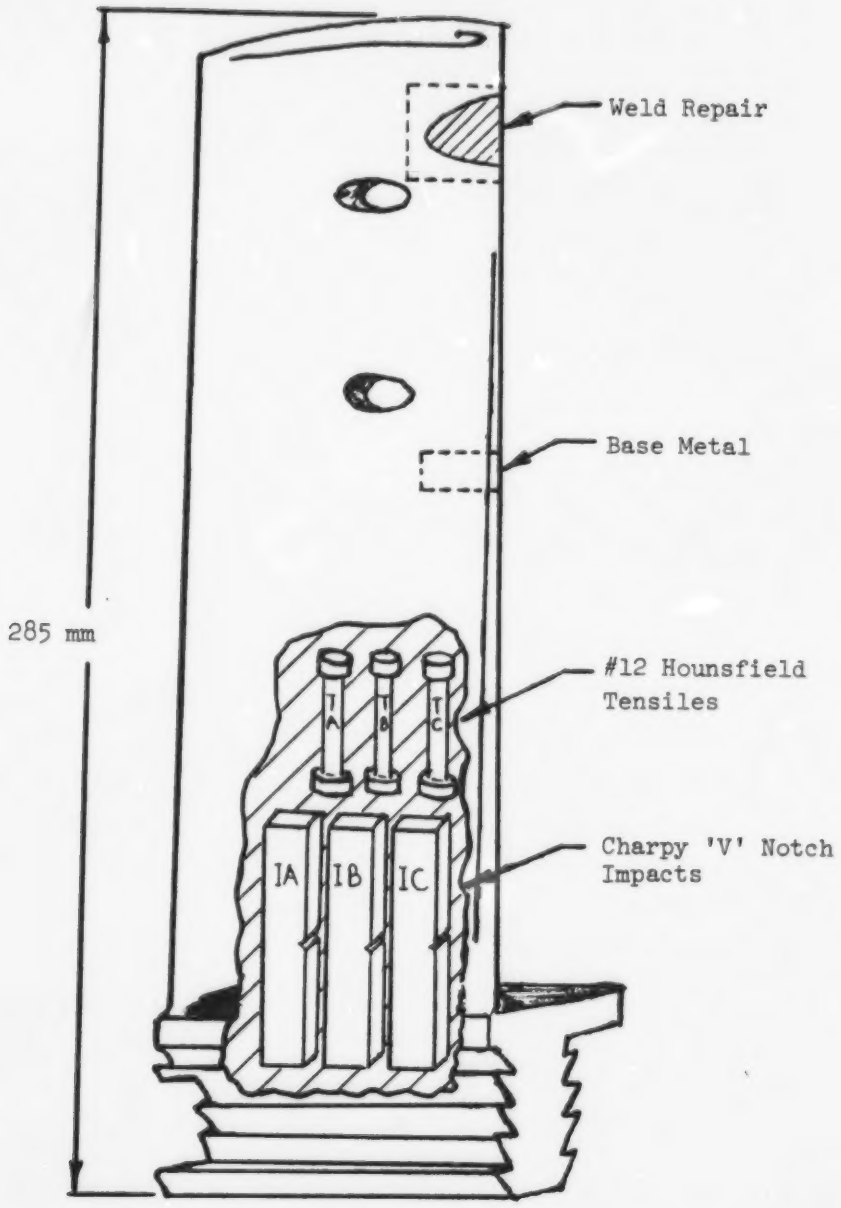
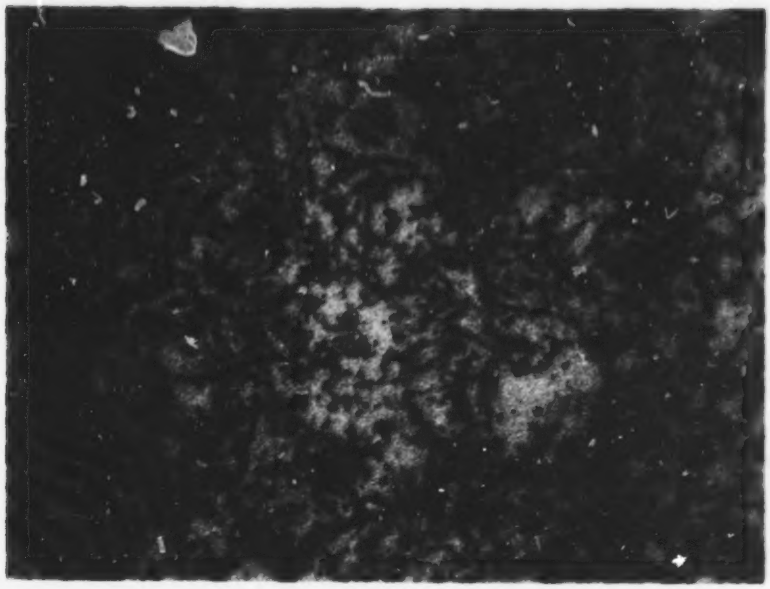
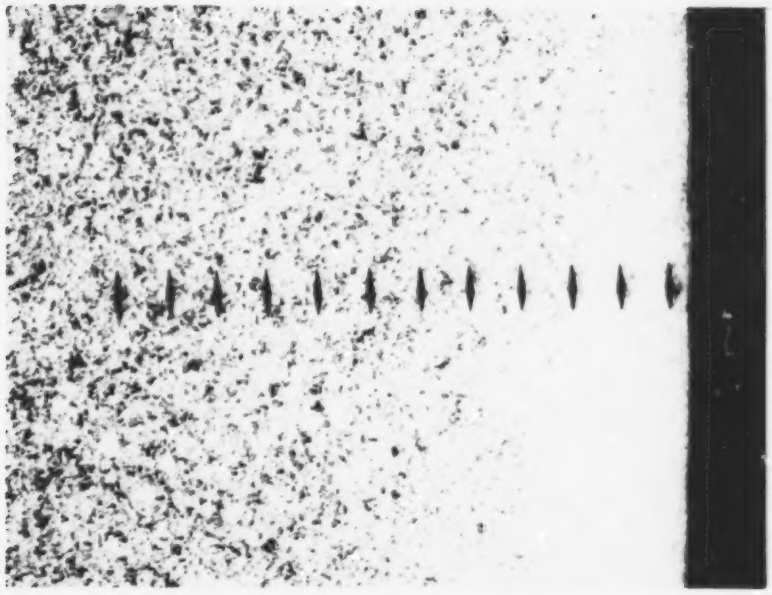



FIGURE 7

METALLOGRAPHIC AND MECHANICAL TESTING
SAMPLE REMOVAL FROM BLADE "C"



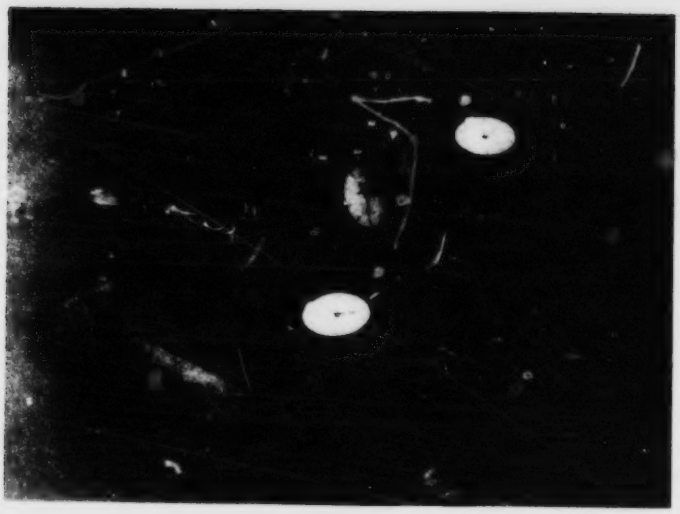
8a - Base Metal Microstructure (1000X Mag)



8b - Exposed Edge Examination (100X Mag)

**FIGURE 8**

**METALLOGRAPHIC EXAMINATION OF THE BASE METAL (BLADE C)**



9a - A Turbine Blade is Shown Clamped Into the Jig

9b - Contact Points of Dial Indicators on the Blade

**FIGURE 9**

**TURBINE BLADE DISTORTION MEASURING JIG**